The Collaborative Cube Puzzle: A Comparison of Virtual and Real Environments

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ABSTRACT
In this study we compared collaboration on a puzzle-solving task carried out by two persons in a virtual and a real environment. The task, putting together a cube consisting of different coloured blocks in a 'Rubiks' cube-type puzzle, was performed both in a shared virtual environment (VE) setting, using a Cave-type virtual reality (VR) system networked with a desktop VR system, and with cardboard coloured blocks in an equivalent real setting. The aims of the study were to investigate collaboration, leadership and performance in the two settings. We found that the participants contributed unequally to the task in the VE, and also differences in collaboration between the virtual and the real setting.

Keywords
Virtual reality, collaboration, presence, co-presence, virtual environments, leadership.

INTRODUCTION
In this study, we are interested in how two people work together on two different types of virtual reality (VR) systems to solve a task with virtual objects – putting together blocks to solve a puzzle – and to compare this with how they solve the same task face-to-face in a 'real' setting. The task was selected in order to investigate how people interact with each other in virtual environments (VE's), and because virtual environments are said to lend themselves to tasks that involve interaction with spatially complex 3-D environments.

The experimental setting was a collaboration in a virtual environment between one person on a Cave-type system, in this case a so-called 3D-Cube with five projection walls, and the other person on a desktop system. In the real setting, the collaboration involved face-to-face interaction with similar size blocks or cubes.

In our study, we were focusing on the following questions or hypotheses:

- We expected, in line with results from previous studies [3], a difference between Cube and desktop, such that both presence and co-presence would be higher for the Cube, and that presence and co-presence would co-vary.
- We also expected to find a correlation between the joint experience of collaboration and the perceived difference in the partners' respective contribution to the task.
- Concerning performance of the task, we expected an order effect such that the improvement of the virtual task with experience from the real task would be greater than the improvement of the real task with experience from the virtual task.
- We also expected to find that there would be a greater degree of collaboration when undertaking the task the second time around.

BACKGROUND AND PREVIOUS STUDIES
A previous study by Slater et al [3] of a puzzle-solving task with three participants found that presence and co-presence were correlated, and that leadership varied between a virtual setting in which the more 'immersed' participant was singled out as the 'leader' as against the same task performed in the 'real' setting where no one was singled out as the 'leader'. In a previous study of ours which examined

presence, co-presence and collaboration and compared a task on two VR systems with different levels of immersion (desktop vs. Cave-type system), we found that although participants were able to make discriminating judgements about their own experience (presence and co-presence) of the different VR systems, they were unable to make discriminating judgements about their joint experience (collaboration and communication) of the two systems (Axelsson et al. [1], cf. the similar finding in the study comparing collaborative work in a VE with and without haptic interaction in a block-moving task by Sallnäs et al. [2]). These studies have indicated a) that there is a need for a closer examination of the relationship between presence, co-presence, leadership and collaboration for different types of tasks and with different types of VR systems and b) that there is a need to investigate the differences between collaboration and communication in VE's as against 'real' world settings more generally.

TECHNICAL DESCRIPTION AND STUDY DESIGN

The participants used two VR systems for the task; a Cave-type system and a desktop system.

The Cave-type system that was used was a 3x3x3 meter TAN 3D Cube with stereo projection on five walls (no ceiling). The application was run on a Silicon Graphics Onyx2 Infinity Reality with 14MIPS R10000 processors at 250 MHz, 2GB RAM and 3 graphics pipes. The participants wore Crystal Eyes shutter glasses and used a dVise 3-D mouse for navigation. A Polhemus magnetic tracking device tracked both the glasses and the hand. The software that was used was dVise 6.0 supported by the Performer renderer. According to measurements carried out by the Performer renderer during the trial, the frame rate was at least 30 Hz.

The desktop system consisted of a Silicon Graphics O2 with one MIPS R10000 processor and 256MB RAM and a 19-inch screen, again with dVise 6.0 software. An ordinary mouse was used for navigation. The frame rate during the task, again according to the Performer renderer, was at least 20 Hz.

These two VR systems were then networked, so that the participants were physically in two separate rooms while working together in the VE. In both systems, users were represented by identical human-like avatars (the standard avatar in the dVise software system) and could communicate via headsets (so that their hands were free). The movement of the avatars was fixed within the limit of the floor and eye level to avoid participants going through the floor or flying up into the air.

The task was to solve a puzzle involving 8 blocks with different colours on different sides and to rearrange the blocks such that each side would display a single colour (i.e. 4 squares of the same colour on each of the six sides). The task was therefore similar to – but less complex than – the popular Rubik's cube puzzle which involves 9 squares on each side. In our trials the squares were 30 cm along each edge.

Participants were given a maximum amount of 20 minutes to solve the puzzle each time, both in the VE and with the real cubes. There were 88 (voluntary) participants in the trials, and thus 44 groups of two persons working on the task. 22 groups carried out the tasks first in the virtual and then in the real setting, and the other 22 groups were given the tasks in the reversed order – first the real and then the virtual task. We used a mixed group of age, sex, computer skills and VR experience, so that there were 53 men and 35 women between the age of 20 and 56, (*M*=32, SD=9).

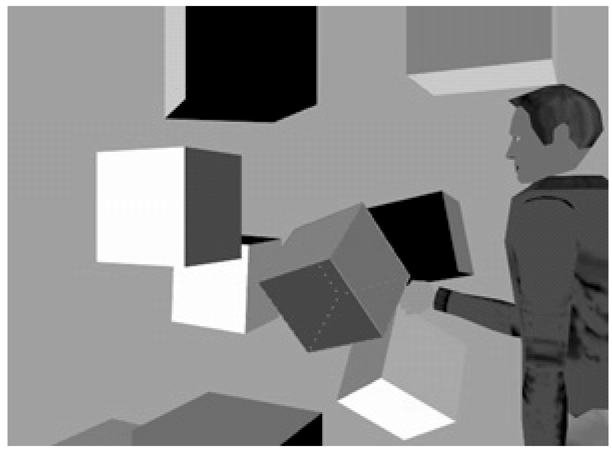

Fig. 1: beginning the task.

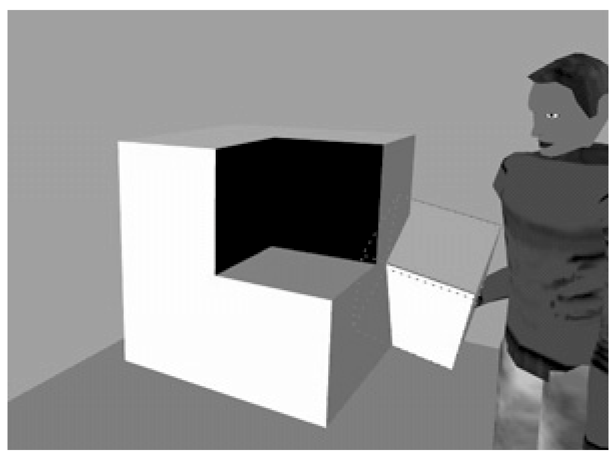

Fig. 2: completing the task

In the Cube system, participants could move the blocks or cubes by putting their hand into the virtual cube and pressing on the button of the 3-D mouse (please note that Cube will be capitalized when referring to the VR system and written with lower-case 'c' for the blocks). Participants could not use the other buttons on the 3-D mouse as they often can in other systems: navigation was purely by moving around physically and gesturing with the 3-D mouse (navigation by ’flying’ would detract from the task in this case).

On the desktop system, participants could navigate by moving the middle mouse button and select the cubes by clicking on the cube with the left mouse button. To move the cubes, they had to keep the right mouse button pressed and move the mouse in the desired direction. They could also rotate the cube by pressing the right mouse button combined with the shift key.

RESULTS

The participants were asked both qualitative and quantitative questions. In this paper, we report only on the quantitative results, even though some qualitative data are mentioned in the conclusions.

Performance

We measured the time each group used to solve the task, both in the real and the virtual setting. The groups that did not complete the task within the time limit of 20 minutes were interrupted and not given a specific time measure. All tasks were performed by a total of 22 groups.

	No of groups completed	Mean time*
Virtual first	6	15 min
Virtual second	16	13 min

Table 1: Virtual task performance.

	No of groups completed	Mean time*
Real first	21	8 min
Real second	22	6 min

Table 2: Real task performance.

* Only the groups that completed the task are included.

In the virtual setting, the groups that did the virtual task after the real task performed much better than the groups that did the virtual task first (Fig. 3).

In the real setting, the groups that did the real task after the virtual task performed slightly better than the groups that did the real task first (Fig. 4).

Also, the difference between the groups that did the virtual task first and the groups that did the virtual task after the real task was *greater* than the difference between the groups that did the real task first and the groups that did the real task after the virtual task. (Comparing the gray areas in fig. 3 and fig. 4).

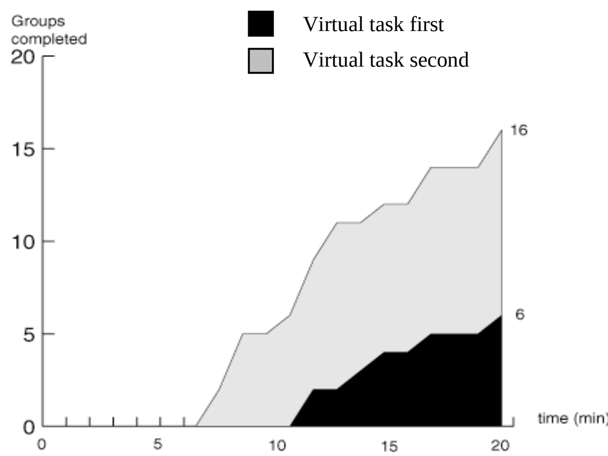

Fig. 3: Number of groups that completed the task in VR.

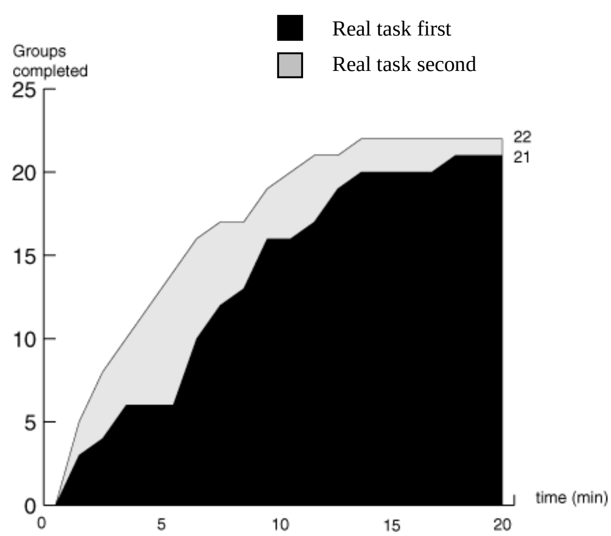

Fig. 4: Number of groups that completed the task in Real.

Presence

In order to find out how present the subjects felt in the two VR systems we asked two similar questions about how much the subjects had a sense of being in the same room as the cubes (on a scale of 1-5 where 1 = to a very small extent and 5 = to a very high extent). These two questions were then put together as one measure of presence (hence a total minimum of 2 and a maximum of 10).

An ANOVA showed that there was a significant difference between the environments $F(1, 86) = 147.21$, $MS_E = 2.42$, $p < .001$ ($\omega^2 = .62$) such that the subjects reported a stronger presence in the Cube (M = 8.50, SD = 1.17) than at the desktop (M = 4.48, SD = 1.86).

There was no order effect between the virtual and the real task. This means that the groups that did the virtual task after the real task were not affected by their previous experience from the real task concerning presence.

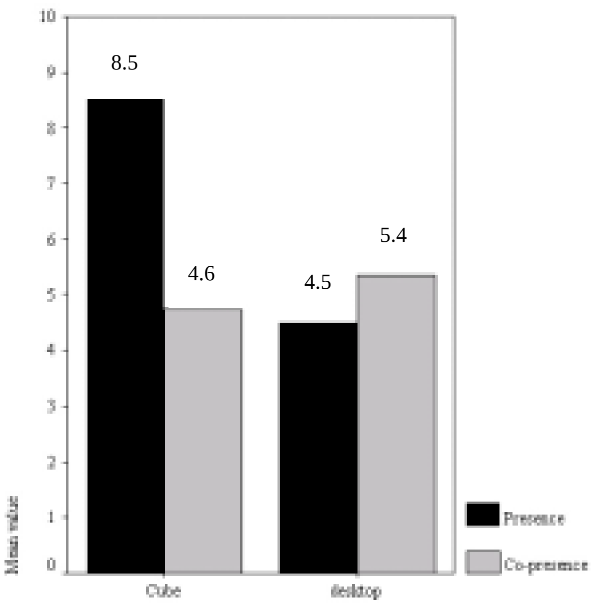

Fig. 7: Presence and Co-presence in Cube and desktop.

Co-presence

Next, in order to find out how co-present the subjects felt in the VR-system, we asked two similar questions about how much the subjects had a sense of being in the same room as their partner (on a scale of 1-5 where 1 = to a very small extent and 5 = to a very high extent). These two questions were then put together as one measure of co-presence (hence a total minimum of 2 and a maximum of 10).

Subjects reported an equally strong co-presence in the Cube (M = 4.75, SD = 2.00) and at the desktop (M = 5.36, SD = 1.99). There was no significant difference between them.

The corrrelational analyses showed that there was a difference between the two VR systems such that presence and co-presence were correlated in the desktop environment ($r = .74$; $p < .001$), but not in the Cube.

Again, there was no order effect between the virtual and the real task. This means that the groups that did the virtual task after the real task were not affected by their previous experience from the real task concerning co-presence.

Leadership and Contribution to the Task

Three questions were asked to allow the subjects evaluate their own and their partners activity: "How would you evaluate your and your partners level of activity when it came to solving the task", "To what extent did you and your partner contribute to placing the cubes" and "Who talked the most, you or your partner". The first question concerned activity in general, the second the contribution in placing the cubes and the third the amount of verbal contribution. Evaluations were given in percentage terms where both partners had to add up to 100, i.e. if they were equal they would add up 50-50.

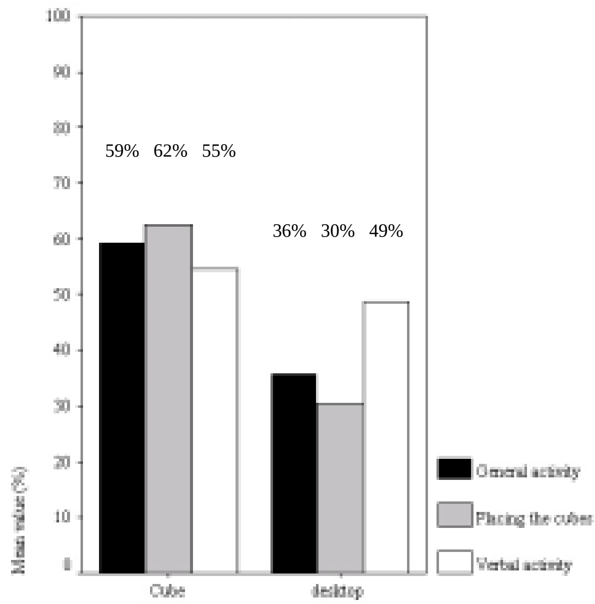

Fig. 8: Contribution to the task on the two VR systems.

The largest difference between Cube and desktop was found in the estimation of contribution in placing the cubes, such that both the Cube person (M = 62.49, SD = 14.50) and the desktop person (M = 30.34, SD = 17.99) thought that the person in the Cube was more active (note that the mean values are self estimations). Both the Cube person (M = 58.75, SD = 13.12) and the desktop person (M = 35.68, SD = 15.72) also evaluated the person in the Cube to be more active in general. The smallest difference between Cube and desktop was found in the estimation of verbal activity, such that both the Cube person (M = 54.55, SD = 7.53) and the desktop person (M = 48.64, SD = 8.52) estimated that the both participants contributed in a more equal way.

An ANOVA showed that there was a significant difference between the groups for all the questions concerning activity. For general activity $F(1, 86) = 55.82$, $MS_E = 209.72$, $p < .001$ ($\omega^2 = .38$), for contribution in placing the cubes $F(1, 85) = 83.96$, $MS_E = 267.68$, $p < .001$ ($\omega^2 = .49$), and for verbal activity $F(1, 86) = 11.88$, $MS_E = 64.64$, $p = .001$ ($\omega^2 = .11$)

Also, both partners agreed that their contributions were different, and they agreed about what this difference in their own and their partner's contribution consisted of in percentage terms.

The correlational analyses showed that there was a strong relation between the two partners' evaluations such that when the Cube person reported a high value for his/her own contribution, the desktop person reported a low. This was the situation for the general activity ($r = -.68$; $p < .001$) and for contribution placing the cubes ($r = -.61$; $p < .001$), but not for verbal activity.

In the real world setting, there was no significant difference between participants on any of the three measures for activity; that is, both partners said that they contributed equally to solving the task in all three respects.

Collaboration

We also asked the participants to evaluate collaboration: "To what extent did you experience that you and your partner collaborated?" (on a scale of 1-5 where 1 = to a very small extent and 5 = to a very high extent). The results showed that subjects felt that they collaborated to a high degree in both desktop and Cube environments. There was no significant difference between the two groups. Nor was there a significant difference between subjects in terms of collaboration in the 'real' world setting. As shown by a T-test there was, however, a significant difference between VR and 'real' $T(87) = 2.60$, $p < .05$, such that subjects felt that they collaborated more in the real task ($M = 4.02$, $SD = .99$) than in the virtual task ($M = 3.67$, $SD = 1.09$).

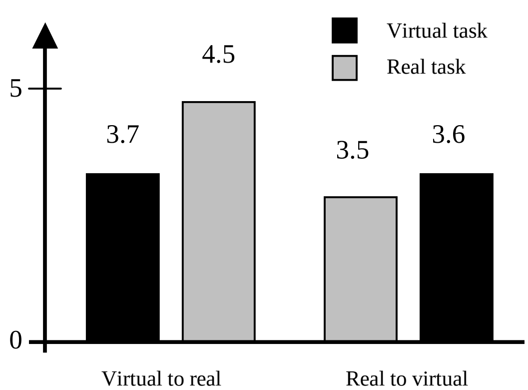

Fig. 9: Collaboration order effect

The groups that did the real task after the virtual task reported a higher degree of collaboration in the real task than in the virtual task. A T-test showed that there was a significant difference $T(43) = 5.52$, $p < .001$, such that subjects with experience from the virtual task reported a higher degree of collaboration in the real task ($M = 4.57$, $SD = .66$) than in the virtual task ($M = 3.73$, $SD = 1.00$).

For the groups that did the real task before the virtual task there was no significant difference in collaboration.

Also, the groups that did the real task *with* experience from the virtual task reported a higher degree of collaboration in the real task ($M = 4.57$, $SD = .66$) than the groups that did the real task *without* experience from the virtual task ($M = 3.48$, $SD = .98$). An ANOVA showed that there was a significant order difference between the groups such that $F(1, 86) = 37.67$, $MS_E = .70$, $p < .001$ ($\omega^2 = .29$).

We also asked a question about enjoyment of collaboration that showed the same results.

For the virtual task there was no order effect in collaboration.

CONCLUSIONS

Performance

In relation to performance, from figures 1 and 2, we can see that a) there was a great similarity in performance of the real task undertaken before and after the virtual, while there was a great difference in performance of the virtual task as to whether it was undertaken before or after the real, and b) that the participants brought more improvement to the performance of the virtual task after undertaking the task in real than the other way around. (We say 'improvement' because not all groups completed the task so that we cannot show a single measure of 'improvement' in minutes, but there is a clear improvement if we take time and number of successful groups together).

It should be mentioned that better performance in the 'real' world than in the VE should not be regarded as an indication that VR technology is not suitable for this type of task: first, because it may be that the reason for using VR technology may be to enable users to do what they cannot do in the 'real' world – for example, the cubes can be modified more easily, they do not 'weigh' anything, etc. Secondly, the reason for using networked VE's may be to allow users to work together at a distance – in this case, a more appropriate comparison might therefore have been to compare collaborative VE's with videophones, or with two people collaborating on the cube puzzle by giving each other instructions about how to simultaneously move the 'real' cubes (of which they would each have to have a copy) over the telephone.

Presence and co-presence

As expected that there was a stronger sense of 'presence' in the Cube than on the desktop system.

However, there was no significant difference between the two systems in relation to co-presence, but participants in the Cube reported a high degree of presence without a high degree of co-presence. This is surprising because participants did report differences in 'presence', and also because Slater et al. [3] (in a study of two participants on a desktop system and one participant with an HMD, and with no manipulation of objects) found a significant correlation between 'presence' and 'co-presence'. The explanations for this could be a) that participants in the Cube had a greater sense of interaction with the objects, and thus their interaction with their partners was less important than in the study of Slater et al.; or b) that participants on the desktop had an equally detached view of the cubes and of their partner, whereas for Cube participants the cubes where more immediate.

We can note, from the qualitative questions, that participants generally misperceived what type of VR system their partner was working on: that is, persons in the Cube tended to think that their partner was also using a Cube or immersive environment like their own, and desktop persons thought their partners were also using a desktop system.

Leadership

In relation to leadership, which can be defined, for present purposes, as contributing the greater share to the task, we found that participants in the Cube were evaluated by both partners as being more active in the task generally and contributing more to placing the cubes, as well as in the share of communication.

This point can spelled out in more detail for emphasis: in terms of contribution to the task, both partners agreed about their share of contribution to the task – that is, they both agreed about what they contributed and about what their partners contributed. They also agreed about the difference in their contributions, and there was agreement that this difference applied in different measure to the share in overall contribution, share in placing the cubes, and share of communication.

It should be noted that this agreement existed despite the fact that partners made this judgement in an environment in which they were carrying out the task independently of each other, i.e. not face-to-face.

This result could be expected inasmuch as in previous studies, leadership has been correlated with technological advantage in being more immersed [3] and has also been correlated with being the navigator in a task where the two partners are equally immersed [1]. In our study, both the different levels of immersion and the interaction devices (3D mouse vs. conventional mouse) may be responsible for this effect.

In the real task participants regarded themselves and their partners as being equally active for all three questions. This was expected in the light of the study of Slater et al. [3], which found a similar asymmetry between the more immersed and the less immersed partner in the 'virtual' task – with, in their case, as in ours, partners who did not know each other before – and the same task carried out in a 'real' world setting where there was similarly no leader.

The fact that participants were more 'unequal' in the virtual task than in the real task could be regarded negatively. But it is important to point out that this is not necessarily so: collaboration in the sense of 'equal contribution' may be preferred, but it is not always conducive, for example, to working together. Short, Williams and Christie [5], among others, have shown that dividing tasks in computer-mediated-communication (which may also involve fewer distracting social cues) can lead to faster and more focused task performance.

The task we examined in this study involved a high degree of physical interaction – at least for the immersed person - with the VE, as well as a high degree of interaction with virtual objects. It produced different results, as we have indicated, from, among others – both studies that involved mainly verbal collaboration [3] and from studies that involved a mainly 'physical' task [2]. Since these are different tasks on different VR systems and with different modes of collaboration, they are not strictly comparable. But they show that systematic investigation of the issues discussed – presence, co-presence, leadership and collaboration – and disaggregating the various factors responsible for these features of VE's, will be highly rewarding.

Collaboration

In terms of collaboration, the difference, as we have seen, was between 'virtual' and 'real': participants felt that there was more collaboration on the task in the 'real' as opposed to the virtual setting. There was no difference between Cube- and desktop participants. A possible explanation for this is that face-to-face interaction offers 'richer' communication possibilities than communication via different communications media (for a review of studies of media 'richness' and 'social presence', see van Dijk, [4]). It is also interesting to compare this study with a previous study of ours which compared collaboration of two co-located partners in the Cube as against two partners solving the same puzzle sitting next to each other on a desktop system: in that study, we found that desktop partners thought they were collaborating to a greater extent than Cube partners – even though the Cube partners reported a greater degree of co-presence in the environment than desktop partners [1].

If we look at leadership and collaboration together, we can see that in the virtual setting, where participants assessed their contributions unequally, they also reported a lower degree of collaboration. In the real setting, on the other hand, they assessed their respective contributions equally, and also reported more collaboration. At this point it may therefore be asked: is the 'division of labour' (between the Cube participant and the desktop participant) considered as a less collaborative way of performing the task? Put differently, would 'greater equality' be felt to be more collaborative?

If we assume that more equal contributions and higher degrees of collaboration are good for co-working on a task in VE's, then we can see that in this case, the virtual setting and/or the difference between the two types of systems were responsible for a more unequal and less collaborative mode of co-working. Again, this can be put the other way around and from a somewhat different viewpoint: technologically mediated communication introduces asymmetries into interpersonal interaction and/or takes away social cues. These are issues which must be taken into account in the design of collaborative VE's.

What is interesting here is that: both participants had similar evaluations of 'co-presence' in the VE, and they were able to agree on the distinction between their respective contributions. Put differently, participants had a shared perception of co-presence for the virtual task – and yet they also had a shared perception of the distinctive collaborative parts that they played in this task.

Virtual to Real versus Real to Virtual

Surprisingly, there was no effect of the order in which the tasks were carried out – on presence, co-presence, or contribution to the task. In other words, the experience that participants had in one setting did not make any difference to their estimation of presence, co-presence or contribution to the task in the other setting.

However, there was an order effect when it came to collaboration: the perceived collaboration in the real task increased if the virtual task was first, but surprisingly – and against our hypothesis – it did not increase in the virtual setting if the real task was first. (This also applies to the enjoyment of collaboration).

This suggests that, in terms of collaboration, people bring their joint experience from the virtual to the real task. That is to say, the shared and for most users novel experience in the VE seems to have a positive influence on the following experience of collaboration during the real task.

It is interesting that when it comes to performance of the task, the order effect was opposite: the major difference was found between the groups that performed the virtual task with or without prior experience from the real.

In terms of performance we suggest that the participants bring more knowledge about the problem solving from the real to the virtual task than the other way around. This could have to do with the complexity of the virtual environment. In relation to collaboration, however, the novelty of working together virtually may have made a stronger impression than the actual problem solving.

FUTURE WORK

We will analyze audio recordings made during our study and other qualitative data, as well as examining other correlations that were found. An obvious interesting novel direction would be to allow both participants to work on the same type of VR system: would this enhance collaboration? Other configurations of the study can be envisaged, but a start has been made in examining a highly involving type of task – the most physically 'interactive' task, to the best of our knowledge - in a collaborative Cave-type VE setting.

ACKNOWLEDGEMENTS

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